

Testing astroparticle physics with the Fermi Large Area Telescope

Aldo Morselli^a *on behalf of the Fermi LAT collaboration*

^aINFN Roma Tor Vergata

Our understanding of the Universe today includes overwhelming observational evidence for the existence of an elusive form of matter that is generally referred to as dark. Although many theories have been developed to describe its nature, very little is actually known about its properties. Since its launch in 2008, the Large Area Telescope, onboard the Fermi Gamma-ray Space Telescope, has detected by far the greatest number ever of gamma rays, in the 20MeV 300GeV energy range and electrons + positrons in the 7 GeV- 1 TeV range. This impressive statistics allows one to perform a very sensitive indirect experimental search for dark matter. I will present the latest results on these searches.

1. The Cosmic Ray Electron spectrum

Recently the experimental information available on the Cosmic Ray Electron (CRE) spectrum has been dramatically expanded as the *Fermi* LAT Collaboration [1] has reported a high precision measurement of the electron spectrum from 7 GeV to 1 TeV performed with its Large Area Telescope (LAT) [2], [3]. The spectrum shows no prominent spectral features and it is significantly harder than that inferred from several previous experiments. These data together with the PAMELA data on the rise above 10 GeV of the positron fraction [4] are quite difficult to explain with just secondary production [5],[6], [7].

The temptation to claim the discovery of dark matter from detection of electrons from annihilation of dark matter particles is strong but there are competing astrophysical sources, such as pulsars, that can give a strong flux of primary positrons and electrons (see [8], [9], [10], [11] and references therein). At energies between 100 GeV and 1 TeV the electron flux reaching the Earth may be the sum of an almost homogeneous and isotropic component produced by Galactic supernova remnants and the local contribution of a few pulsars with the latter expected to contribute more and more significantly as the energy increases.

Two pulsars, Monogem, at a distance of 290 pc and Geminga, at a distance of 160 pc, can give a

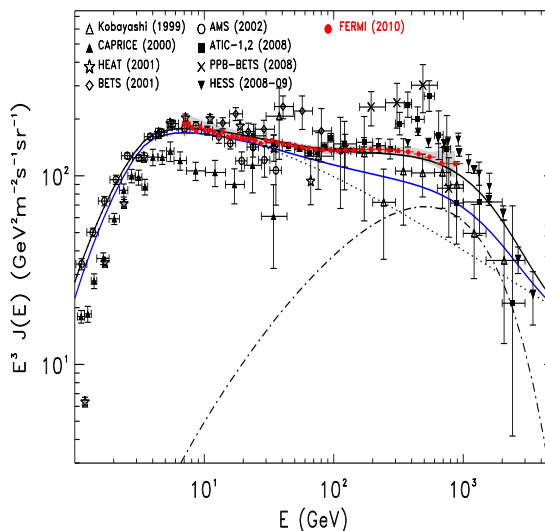


Figure 1. Cosmic ray electron + positron spectrum as measured by *Fermi* Large Area Telescope for one year of observations (filled circles), along with other recent high energy results. The gray band represents systematic errors on the *Fermi* LAT data [2], [3]. The solid line is the computed conventional GALPROP model but with an injection index $\Gamma = 1.6/2.7$ below/above 4 GeV (dotted line). An additional component with an injection index $\Gamma = 1.5$ and exponential cut-off is shown by the dashed line. Blue line shows e^- spectrum only.

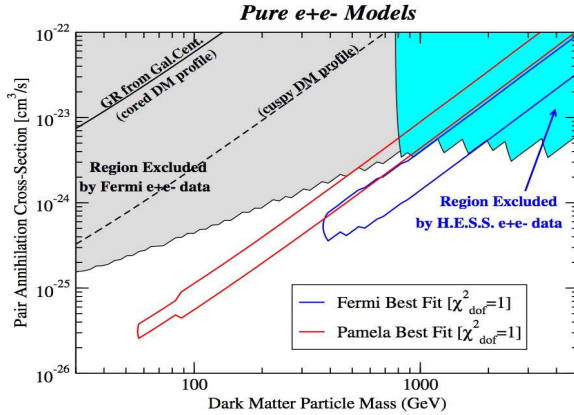


Figure 2. The parameter space of dark matter particle mass versus pair-annihilation rate, for models where dark matter annihilates into monochromatic e^\pm . Models inside the regions shaded in gray and cyan over-produce e^\pm from dark matter annihilation with respect to the *Fermi* LAT and H.E.S.S. measurements, at 2σ level. The red and blue contours outline the regions where the χ^2 per degree of freedom for fits to the PAMELA and *Fermi* LAT data is less than 1.

significant contribution to the high energy electron and positron flux reaching the Earth and with a set of reasonable parameters of the model of electron production the *Fermi* LAT data and the PAMELA positron fraction can be well fit fraction [4] (see figure 1). However we have a lot of freedom in the choice of these parameters because we still do not know much about these processes, so further study on high energy emission from pulsars is needed in order to confirm or reject the pulsar hypothesis.

Nevertheless a dark matter interpretation of the *Fermi* LAT and of the PAMELA data is still an open possibility. Figure 2 shows the parameter space of dark matter particle mass versus pair-annihilation rate, for models where dark matter annihilates into monochromatic e^\pm [11]. The preferred range for the dark matter mass lies between 400 GeV and 1-2 TeV, with larger masses increasingly constrained by the H.E.S.S. results [12]. The required annihilation rates, when employing a particular dark matter den-

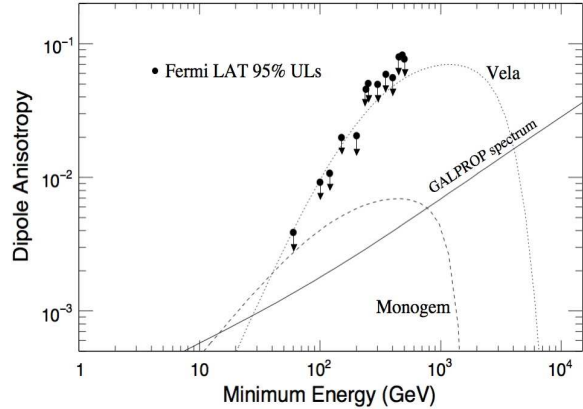


Figure 3. Dipole anisotropy δ versus the minimum energy for GALPROP (solid line), Monogem source (dashed line), and Vela source (dotted line). The 95% Upper limit's confidence level from the data is also shown with circles. The solar modulation was treated using the force-field approximation with modulation potential $\Phi=550$ MV.

sity profile imply typical boost factors ranging between 20 and 100, when compared to the value $\langle\sigma v\rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{sec}$ expected for a thermally produced dark matter particle relic.

How can one distinguish between the contributions of pulsars and dark matter annihilations? Most likely, a confirmation of the dark matter signal will require a consistency between different experiments and new measurements of the reported excesses with large statistics. The observed excess in the positron fraction should be consistent with corresponding signals in absolute positron and electron fluxes in the PAMELA data and all lepton data collected by *Fermi* LAT. *Fermi* LAT has a large effective area and long projected lifetime, 5 years nominal with a 10 years goal, which makes it an excellent detector of cosmic-ray electrons up to ~ 1 TeV. Future *Fermi* LAT measurements of the total lepton flux with large statistics will enable distinguishing a gradual change in slope as opposed to a sharp cutoff with high confidence [13]. The latter can be an indication in favor of the dark matter hypothesis.

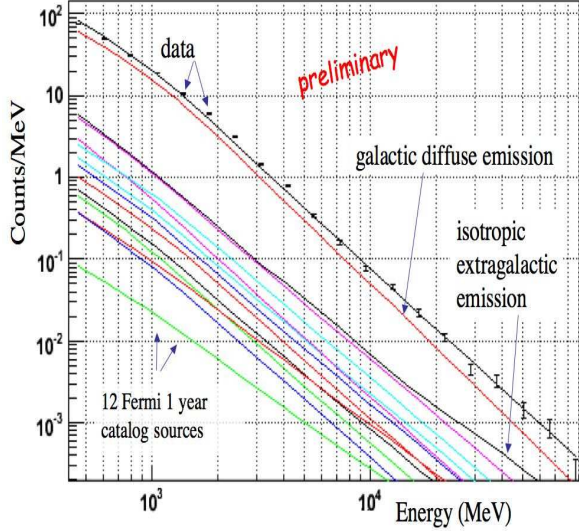


Figure 4. Counts spectra from the likelihood analysis of the *Fermi* LAT data (number of counts vs reconstructed energy) in a $7^\circ \times 7^\circ$ region around the Galactic Center (number of counts vs reconstructed energy).

Another possibility is to look for anisotropies in the arrival directions of the electrons. The *Fermi* LAT) detected more than 1.6 million cosmic-ray electrons/positrons with energies above 60 GeV during its first year of operation. The arrival directions of these events were searched for anisotropies of angular scale extending from $\sim 10^\circ$ up to 90° , and of minimum energy extending from 60 GeV up to 480 GeV. An upper limit for the dipole anisotropy has been set to 0.5 - 10% depending on the energy [14].

The levels of anisotropy expected for Vela-like and Monogem-like sources (i.e. sources with similar distances and ages) seem to be greater than the scale of anisotropies excluded by the results (see figure 3). However, it is worth to point out that the model results are affected by large uncertainties related to the choice of the free parameters.

2. The gamma-ray signals

A strong leptonic signal should be accompanied by a boost in the γ -ray yield providing a distinct

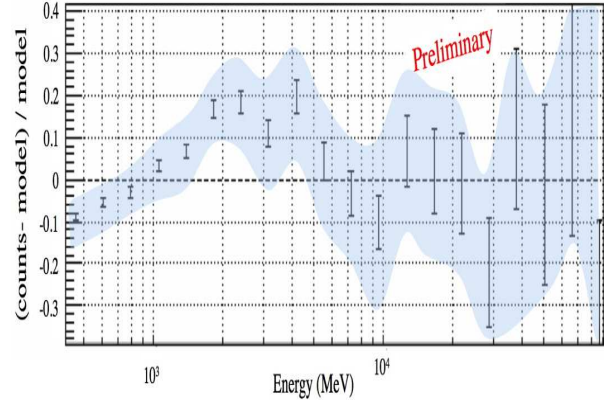


Figure 5. Residuals $((\text{exp.data} - \text{model})/\text{model})$ of the above likelihood analysis. The blue area shows the systematic errors on the effective area.

spectral signature detectable by *Fermi* LAT.

The Galactic center (GC) is expected to be the strongest source of γ -rays from DM annihilation, due to its coincidence with the cusped part of the DM halo density profile [15], [16]. A preliminary analysis of the data, taken during the first 11 months of the Fermi satellite operations, is shown in figures 4 and 5. The reported results were obtained with a binned likelihood analysis, performed by means of the tools developed by the *Fermi* LAT collaboration (gtlike, from the Fermi analysis tools [17]).

In order to analyze the diffuse and point-source gamma-ray emission in this region using a maximum likelihood method for the LAT data, a model of the already known sources and the diffuse background should be built. The model in use for the presented analysis contains 11 sources in the *Fermi* 1 year catalog [18] which are located within or very close to the considered region being analyzed. These sources have a point-like spatial model and a spectrum in the form of a power-law. The model also contains the diffuse gamma-ray background which is made of two components: 1) *the Galactic Diffuse gamma-ray background*. The observed Galactic Diffuse emission was modeled by means of the GALPROP code (model number 87XexphS) [19] and [20]. 2) *the Isotropic*

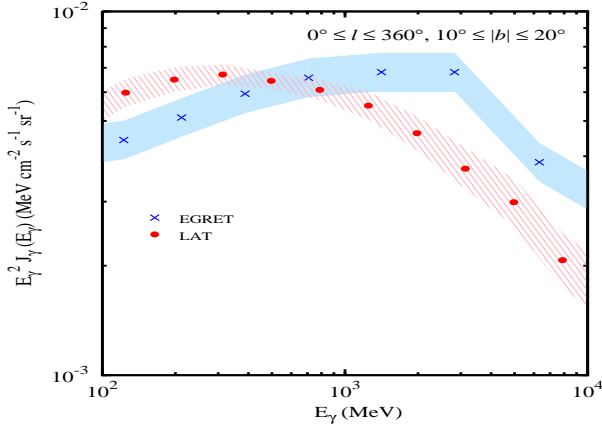


Figure 6. Diffuse emission intensity averaged over all Galactic longitudes for latitude range $10^\circ \leq |b| \leq 20^\circ$. Data points: *Fermi* LAT, red dots; EGRET, blue crosses. Systematic uncertainties: *Fermi* LAT, red; EGRET, blue.

Background. This component should account for both the Extragalactic gamma-ray emission and residual charged particles. It is modeled as an isotropic emission with a template spectrum.

The diffuse gamma-ray backgrounds and discrete sources, as we know them today, can account for the large majority of the detected gamma-ray emission from the Galactic Center. Nevertheless a residual emission is left, not accounted for by the above models [21].

Improved modeling of the Galactic diffuse model as well as the potential contribution from other astrophysical sources (for instance unresolved point sources) could provide a better description of the data. Analyses are underway to investigate these possibilities.

An excess in gamma-ray from dark matter annihilation also should be seen in the Galactic diffuse spectrum. Figure 6 shows the LAT data averaged over all Galactic longitudes and the latitude range $10^\circ \leq |b| \leq 20^\circ$. The hatched band surrounding the LAT data indicates the systematic uncertainty in the measurement due to the uncertainty in the effective area. Also shown on the right are the EGRET data for the same region

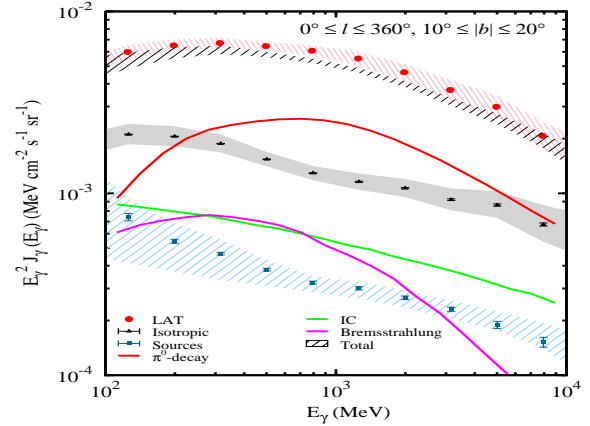


Figure 7. *Fermi* LAT data with model, source, and isotropic components for same sky region of Figure 6

of sky where one can see that the LAT-measured spectrum is significantly softer than the EGRET measurement [22]. Figure 7 compares the LAT spectrum with the spectra of an *a priori* diffuse Galactic emission (DGE) model. While the LAT spectral shape is consistent with the DGE model used in this paper, the overall model emission is too low thus giving rise to a $\sim 10 - 15\%$ excess over the energy range 100 MeV to 10 GeV. However, the DGE model is based on pre-*Fermi* LAT data and knowledge of the DGE. The difference between the model and data is of the same order as the uncertainty in the measured CR nuclei spectra at the relevant energies. Overall, the agreement between the LAT-measured spectrum and the model shows that the fundamental processes are consistent with our data, thus providing a solid basis for future work in understanding the DGE.

3. Dwarf spheroidal galaxies and Clusters of galaxies

Local Group dwarf spheroidal galaxies, the largest galactic substructures predicted by the cold dark matter scenario, are attractive targets for dark matter indirect searches because they are nearby and among the most extreme dark matter dominated environments. With the data taken

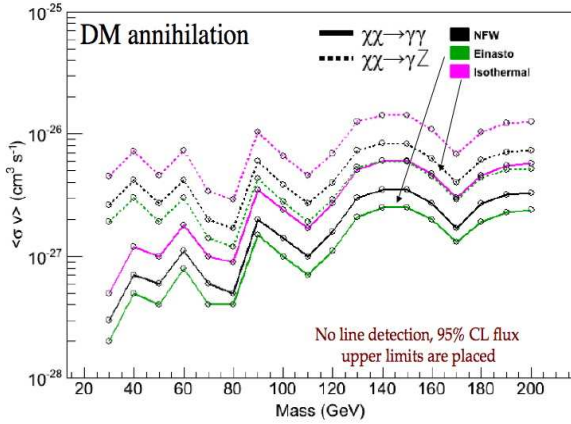


Figure 8. Cross-section limits for various dark matter halo profiles for the annihilation into monochromatic gamma-rays.

during the first 11 months no significant γ -ray emission was detected above 100 MeV from any dwarf galaxies. So we can determine upper limits to the γ -ray flux assuming both power-law spectra and representative spectra from WIMP annihilation. The resulting integral flux above 100 MeV is constrained to be at a level below around 10^{-9} photons $\text{cm}^{-2}\text{s}^{-1}$ [23]. Using recent stellar kinematic data, the γ -ray flux limits can be combined with improved determinations of the dark matter density profiles in 8 of the 14 candidate dwarfs to place limits on the pair annihilation cross-section of WIMPs in several widely studied extensions of the standard model, including its supersymmetric extension and other models that received recent attention. With the present data we are able to rule out large parts of the parameter space where the thermal relic density is below the observed cosmological dark matter density and WIMPs (neutralinos here) are dominantly produced non-thermally, e.g. in models where supersymmetry breaking occurs via anomaly mediation. These γ -ray limits also constrain some WIMP models proposed to explain the *Fermi* LAT and PAMELA e^+e^- data, including low-mass wino-like neutralinos and models with TeV masses pair-annihilating into muon-antimuon pairs. The same kind of analysis can

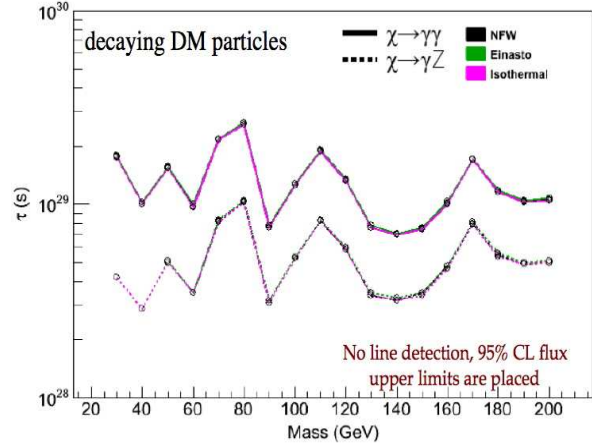


Figure 9. Lifetime limits for various dark matter halo profiles for the decay channel into monochromatic gamma rays.

be made for the clusters of galaxies [24].

Finally a line at the WIMP mass, due to the 2γ production channel, could be observed as a feature in the astrophysical source spectrum [13]. Such an observation would be a “smoking gun” for WIMP DM as it is difficult to explain by a process other than WIMP annihilation or decay and the presence of a feature due to annihilation into γZ in addition would be even more convincing.

Up to now however no lines have been observed and we obtain γ -ray line flux upper limits in the range $0.6 - 4.5 \times 10^{-9} \text{cm}^{-2}\text{s}^{-1}$ [25] and corresponding DM annihilation cross-section and decay lifetime limits shown in figures 8 and 9.

4. Conclusion

Fermi Gamma-ray Space Telescope has opened a new era in DM searches and a large variety of analyses have been developed for clusters of galaxies, DM satellites, DM subhalos, cosmological DM and spectral lines. No significant detections have been made, but constraints that start to probe the available phase space have been put on the annihilation cross-section and decay lifetimes. In addition, several ongoing analyses are now being finalized, including studies of the com-

plicated galactic center region.

The CRE spectrum measured by *Fermi* LAT is significantly harder than what was expected on the basis of previous data. Adopting the presence of an extra e^\pm primary component with ~ 2.4 spectral index and $E_{cut} \sim 1$ TeV allows a consistent interpretation of the *Fermi* LAT CRE data, HESS and PAMELA. Such an extra-component can be produced by nearby pulsars for a reasonable choice of relevant parameters or by annihilating dark matter for models with $M_{DM} \sim 1$ TeV. Improved analysis and complementary observations (CRE anisotropy, spectrum and angular distribution of diffuse γ , DM sources search in γ) are required to possibly discriminate the right scenario. The dark matter origin of any exotic signal has to be confirmed by complementary findings in γ -rays by *Fermi* LAT and atmospheric Cherenkov telescopes, and by LHC in the debris of high-energy proton destructions. On the other hand, if the signal is due to be a conventional astrophysical source of cosmic rays, it will mean a direct detection of particles accelerated at an astrophysical source, again a major breakthrough. However, independent of the origin of these excesses, exotic or conventional, we can expect a very exciting several years ahead of us.

5. Acknowledgments

The *Fermi* LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy and CNES in France for science analysis during the operations phase is also gratefully acknowledged.

REFERENCES

1. W.B.Atwood et al. [Fermi Coll.] ApJ 697 No 2 (2009 June 1) 1071-1102 [arXiv:0902.1089]
2. A.A.Abdo et al. [Fermi Coll.], PRL 102, 181101 (2009) [arXiv:0905.0025]
3. M.Ackermann, et al. [Fermi Coll.], PRD 82, 092004 (2010) [arXiv:1008.3999]
4. O. Adriani et al. [PAMELA Coll.] Nature 458, 607, 2009 [arXiv:0810.4995]
5. A. W. Strong and I. V. Moskalenko, ApJ 509 (1998) 212, ApJ 493 (1998) 694
6. A. Lionetto, A. Morselli, and V. Zdravkovic, JCAP09 (2005) 010 [astro-ph/0502406]
V. S. Ptuskin et al., ApJ 642 (2006) 902
7. A. Morselli, I.Moskalenko, PoS(idm2008)025 [arXiv:0811.3526]
8. A.Boulares APJ 342 (1989) 807-813
9. F. A. Aharonian, A. M. Atoyan and H. J. Völk, Astron. Astrophys. 294 (1995) L41
10. S. Coutu et al., Astrp. Phys. 11 (1999) 429
11. D.Grasso et al. Astropart. Phys. 32 (2009), pp. 140-151 [arXiv:0905.0636]
12. F. Aharonian et al. [H.E.S.S. Coll.], Phys. Rev. Lett. 101 (2008) 261104,
13. E. Baltz et al. , JCAP07 (2008) 013 [arXiv:0806.2911]
14. M.Ackermann et.al. [Fermi Coll.], PRD 82, 092003 [arXiv:1008.5119]
15. A. Morselli at al., Nucl.Phys. 113B (2002) 213
16. A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P. Ullio, Astropart. Phys. 21 (2004) 267 [astro-ph/0305075]
17. <http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/>
18. A.A.Abdo et al. [Fermi Coll.], ApJS 2010 188 405 [arXiv:1002.2280]
19. A.Strong et al., 2004, ApJ 613, 962S
20. A.Strong et al., 2007 Annu. Rev. Nucl. Part. Sci., 57, 285
21. V. Vitale and A. Morselli for the Fermi/LAT Collaboration, 2009 Fermi Symposium [arXiv:0912.3828]
22. A.Abdo et al. [Fermi Coll.], PRL 103, 251101 (2009) [arXiv:0912.0973]
23. A.A.Abdo et al., [Fermi Coll.], ApJ 712 (2010) 147-158 [arXiv:1001.4531]
24. M.Ackermann et al. [Fermi Coll.], JCAP 05, 025 (2010) [arXiv:1002.2239]
25. A.A.Abdo et al., [Fermi Coll.], PRL 104, 091302-08 (2010) [arXiv:1001.4836]